10. Calculations

Needs to Know Criteria
▪ Determine applied pounds per acre of a substance given wastewater flow, concentration, and site acreage
▪ Determine total nitrogen and phosphorus loading rates
▪ Determine COD loading rate
▪ Convert flow data (MGD) to application depth (acre-inches/day)
▪ Determine hydraulic loading rate given flow volume, time, and area of application
▪ Determine acreage required given hydraulic loading rate and flow rate
▪ Determine Irrigation Water Requirement (IWR) given consumptive use, effective precipitation, and irrigation efficiency, and assuming carryover soil moisture and the leaching rate are zero
▪ Determine non-growing season hydraulic loading rate given soil available water holding capacity (AWC), evapotranspiration, and precipitation for the non-growing season, and assuming a leaching rate of zero
▪ Determine plant available nitrogen (PAN) from wastewater data
▪ Determine time of system operation given application depth and application rate
▪ Determine nitrogen and phosphorus crop uptake given crop yield and concentration

A number of calculations are used in the operation and management of a wastewater land application system. Some calculations are made only once and recorded for future reference while others may be performed on a daily basis. In either case, wastewater land application operators should be familiar with the units of measurement, formulas, and calculations presented in the following.

10.1 Include Units of Measurement

It is important that the appropriate units be written with each number used in all calculations. This allows the units to be multiplied and divided as though they were numbers, and it also allows the correct units to be included in the results. Carrying units properly through a calculation serves as a check on the calculation and helps to identify units that need converting.

Inaccurate measurements and calculations can result in erroneous reports and costly operational decisions. Accurate measurements and calculations are important tools for properly controlling and managing wastewater land application processes.

In the following examples, note that all numbers have units with them: square feet, inches, gallons, etc. In several cases, conversion factors have been supplied to simplify the calculations; units are shown for these as well.

10.2 Types of Calculations

A wastewater land application system operator must be familiar with a variety of calculations. In addition to calculations relevant to water flow, there are calculations relevant to the management of soils, crops, fertilizers, constituent loadings, and irrigation equipment.

The following categories of calculations are presented in this section:

- concentration of wastewater constituents
- constituent loading rates
- flow and hydraulic loading rates
- plant available nitrogen calculations
- sodium adsorption ratio (SAR) calculations
- sprinkler hydraulic application rates
- crop yield and crop uptake calculations

Concentration and Constituent Loading Rate Calculations

Concentration is the measurement of the strength of a known constituent or substance (solid, liquid, or gas) dissolved in another substance. Concentration of a substance in wastewater is usually expressed as a percent, as pounds per gallon, as milligrams per liter (mg/L or parts per million [PPM]), or as micrograms per liter (µg/L or parts per billion [PPB]). Concentrations may be expressed in any of these units and may be changed between units if proper conversion factors are used. One of the most frequently used calculations in wastewater mathematics is the conversion of milligrams per liter (mg/L) concentration to pounds (lbs) of constituent loading.

The formulas presented by Equation 10-1 and Equation 10-2 are useful in converting between concentrations and constituent loading rates:

To Convert mg/L to lbs/day:

$$\text{Pounds/day} = \text{concentration (mg/L)} * \text{Flow (million gallons per day)} * 8.34 \text{ lb/gal}$$

or

$$\text{lbs/day} = \text{mg/L} * \text{MGD} * 8.34 \text{ lb/gal}$$

Equation 10-1. Converting mg/L to lbs/day.

To Convert lbs/day to mg/L:

$$\text{Concentration (mg/L)} = \frac{\text{Pounds/day}}{\text{flow (million gallons per day)} * 8.34 \text{ lb/gal}}$$

or

$$\text{mg/L} = \frac{\text{lbs/day}}{\text{MGD} * 8.34 \text{ lb/gal}}$$

Equation 10-2. Converting lbs/day to mg/L.

Example 1: Calculate Concentration, Constituent Loading Rates

The land-applied effluent at a land application site averages:

- 0.2 mg/L of nitrate + nitrite
- 12.3 mg/L TKN
- 5.2 mg/L ammonia
- 3.7 mg/L total phosphate
- 261 mg/L COD.

The 120 acre land application site only operates during the growing season for 184 days out of the year. If the average daily hydraulic loading rate is 0.1 MGD, determine the following:

1. Total N loading rate in pounds per acre per year
2. Phosphorus loading rate in pounds per acre per year
3. Growing season COD loading rate in pound per acre per day

Solution:

1. Nitrogen

Total Nitrogen	= (Nitrate + Nitrite) + TKN
	= 0.2 mg/L + 12.3 mg/L
	= 12.5 mg/L

Note: Recall from Section 1 that *Total Kjeldahl nitrogen* (TKN) is the sum of organic nitrogen and ammonia (see page 1-7).

lbs/day	= (mg/L)(MGD)(8.34)
	= (12.5 mg/L)(0.1 MGD)(8.34 lbs/gal)
	= 10.4 lbs/day
lbs/year	= (10.4 lbs/day)(184 days/year)
	= 1,914 lbs/year N
lbs/acre/year	= (1,914 lbs/year N)/(120 acres)
	= 16.0 lbs/acre/year N

2. Phosphorus

lbs/day	= (mg/L)(MGD)(8.34)
	= (3.7 mg/L)(0.1 MGD)(8.34 lbs/gal)
	= 3.09 lbs/day
lbs/year	= (3.09 lbs/day)(184 days/year)
	= 569 lbs/year P
lbs/acre/year	= (569 lbs/year P)/(120 acres)

= 4.7 lbs/acre/year phosphorus

3. COD

lbs/day = (mg/L)(MGD)(8.34)

= (261 mg/L)(0.1 MGD)(8.34 lbs/gal)

= 218 lbs/day

lbs/acre/day = (218 lbs/day COD)/(120 acres)

= 1.8 lbs/acre/day COD

Hydraulic Loading Rate Calculations

Hydraulic Loading Rate may be measured in inches of wastewater applied to an area in a day (inches/day). To calculate the hydraulic loading rate in inches/day (with flow to the land application field measured in gallons), you must use the following conversion factor: one inch of water per acre (1 ac-in) = 27,154 gallons (Equation 10-3, Figure 10-1).

$$\text{Hydraulic Loading Rate (in/day)} = \frac{\text{Flow (gallons per day)}}{27{,}154\ \dfrac{\text{gallons}}{\text{acre - inch}} * \text{Area (acres)}}$$

Equation 10-3. Calculation of hydraulic loading rate.

Figure 10-1. Acre with one inch of water = 27,154 gallons.

Hourly Hydraulic Loading Rate is inches of wastewater applied to an area of soil in an hour. To calculate *Hourly Hydraulic Loading Rate*, use the Hydraulic Loading Rate formula and convert from inches per day to inches per hour as follows:

$$\text{Hydraulic Loading Rate (in/day)} = \frac{\text{Flow (gallons per day)}}{27{,}154\ \dfrac{\text{gallons}}{\text{acre - inch}} * \text{Area (acres)}} * \frac{1\,\text{day}}{24\ \text{hours}}$$

Example 2: Calculate Hydraulic Loading Rate

What is the hydraulic loading rate for a land application system that pumps 50,000 gallons in one day, equally, over a 4.28 acre site?

$$\text{Hydraulic Loading Rate (in/day)} = \frac{\text{Flow (gallons per day)}}{27{,}154\ \frac{\text{gallons}}{\text{acre - inch}} * \text{Area (acres)}}$$

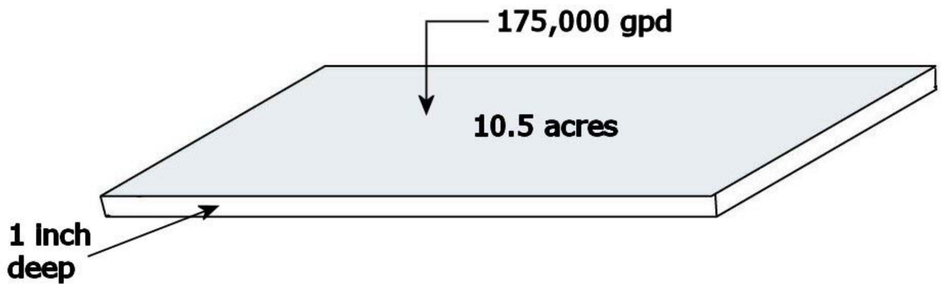
$$\text{Hydraulic Loading Rate (in/day)} = \frac{50{,}000\ \text{(gallons per day)}}{27{,}154\ \frac{\text{gallons}}{\text{acre - inch}} * 4.28\ \text{acres}}$$

$$= \frac{50{,}000\ \text{(gallons per day)}}{116{,}210.6\ \frac{\text{gallons}}{\text{inch}}}$$

$$= \frac{0.43\ \text{inches}}{\text{day}}$$

Example 3: Calculate Hydraulic Loading Rate

What is the hydraulic loading rate for a land application system that pumps 175,000 gallons in one day, equally, over a 10.5 acre site?



$$\text{Hydraulic Loading Rate (in/day)} = \frac{\text{Flow (gallons per day)}}{27{,}154\ \frac{\text{gallons}}{\text{acre - inch}} * \text{Area (acres)}}$$

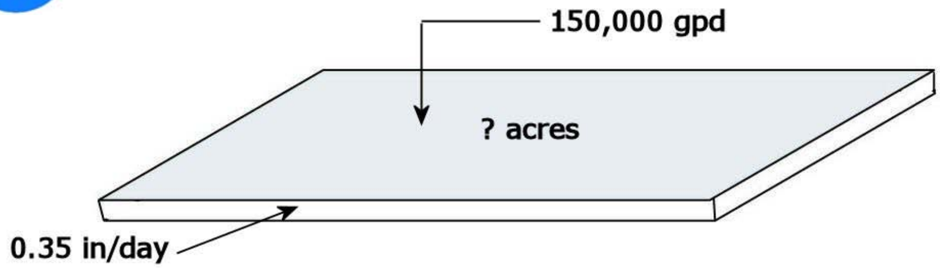
$$= \frac{175{,}000\ \text{(gallons per day)}}{27{,}154\ \frac{\text{gallons}}{\text{acre - inch}} * 10.5\ \text{acres}}$$

$$= \frac{175{,}000\ \text{(gallons per day)}}{285{,}096\ \frac{\text{gallons}}{\text{inch}}}$$

$$= \frac{0.61\ \text{inches}}{\text{day}}$$

Example 4: Calculate Acres Given Hydraulic Loading Rate and Flow

How many acres would be needed to achieve a hydraulic loading rate of 0.35 in/day if the flow is 150,000 gpd?



$$\text{Hydraulic Loading Rate (in/day)} = \frac{\text{Flow (gallons per day)}}{27{,}154\ \frac{\text{gallons}}{\text{acre - inch}} * \text{Area (acres)}}$$

$$0.35\ \text{in/day} = \frac{150{,}000\ \text{(gallons per day)}}{27{,}154\ \frac{\text{gallons}}{\text{acre - inch}} * \text{X acres}}$$

Rearrange the equation to solve for X:

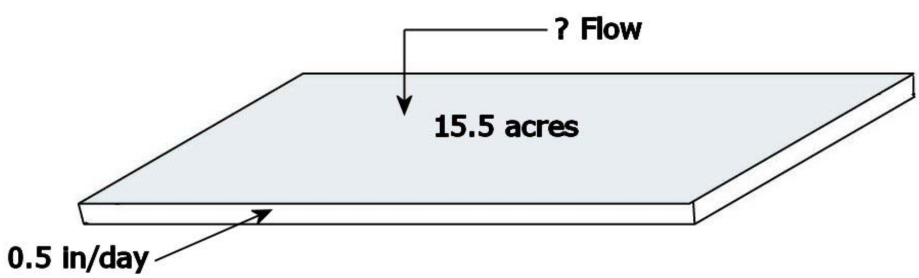
$$\text{X acres} = \frac{150{,}000\ \text{(gallons per day)}}{27{,}154\ \frac{\text{gallons}}{\text{acre - inch}} * 0.35\ \frac{\text{in}}{\text{day}}}$$

$$= \frac{150{,}000\ \text{(gallons per day)}}{9{,}503.2\ \text{gpd/acre}}$$

$$= 15.8\ \text{acres}$$

Example 5: Calculate Flow Given Acreage and Hydraulic Loading Rate

If a land application field is 15.5 acres and receives 0.50 in/day of wastewater, what is the flow in gpd?



$$\text{Hydraulic Loading Rate (in/day)} = \frac{\text{Flow (gallons per day)}}{27{,}154\ \frac{\text{gallons}}{\text{acre - inch}} * \text{Area (acres)}}$$

$$0.5 \text{ in/day} = \frac{X \text{ gpd}}{27{,}154 \frac{\text{gallons}}{\text{acre - inch}} * 15.5 \text{ acres}}$$

Rearrange the equation to solve for X:

$$X \text{ gpd} = 0.5 \text{ in/day} * 27{,}154 \frac{\text{gallons}}{\text{acre - inch}} * 15.5 \text{ acres}$$

$$= 210{,}428 \text{ gpd}$$

As described in Section 7, the permitted irrigation amount (maximum hydraulic loading rate) for the growing season is typically given as the *Irrigation Water Requirement* (IWR). IWR is defined as: any combination of wastewater and supplemental irrigation water applied at rates commensurate to the moisture requirements of the crop, and calculated monthly during the *growing season* (GS).

Calculation methodology for the IWR can be found at the following Web site:

http://www.kimberly.uidaho.edu/water/appndxet/index.shtml

Equation 10-4 is used to calculate the IWR at this Web site:

$$IWR = (CU - Pe) / Ei = IR / Ei$$

Equation 10-4. Calculation of Irrigation Water Requirement (IWR).

- CU is the monthly consumptive use for a given crop in a given climatic area. CU is synonymous with crop evapotranspiration
- Pe is the effective precipitation.
- CU minus Pe is synonymous with the *Net Irrigation Requirement* (IR)
- Ei is the irrigation system efficiency. To obtain the gross irrigation water requirement (IWR), divide the IR by the irrigation system efficiency.
- For permit purposes, the soil carry over moisture and leaching rate are assumed to be zero, and, therefore, are not considered when calculating the IWR.

Example 6: Calculate Growing Season Irrigation Water Requirement (IWR)

Determine the Growing Season Irrigation Water Requirement (IWR) in million gallons (MG) given:

- Location of wastewater land application site: Coeur d’Alene
- Crop: alfalfa
- Irrigation Equipment Efficiency: 80% (0.80)
- Land Application Acreage: 120 acres

1. Determine the IR (Net Irrigation Requirement) by consulting the following Web site (Coeur d’Alene, Alfalfa Hay crop):

http://www.kimberly.uidaho.edu/water/appndxet/index.shtml

The Mean IR for the growing season is given as 625 millimeters (mm)

2. IWR = (625 mm)/(25.4 mm per inch)/(0.80)

   = 30.8 inches

3. Convert to million gallons (MG):

   IWR = (30.8 in)(27,154 gal/ac-in)(120 ac)

   = 100,354,000 gallons = 100.4 MG

As described in Section 1, the *non-growing season* (NGS) hydraulic loading rate is generally limited to the value given by Equation 10-5.

Maximum (NGS) Hydraulic Loading Rate	=	Available Water-Holding Capacity of the Soil	+	Evapotranspiration in the NGS	-	Expected Precipitation in the NGS

Equation 10-5. Calculation of non-growing season hydraulic loading rate.

This loading rate assumes a leaching rate of zero.

Example 7: Calculate Non-Growing Season Hydraulic Loading Rate

Needs To Know!

Determine the Non-Growing Season (NGS) Hydraulic Loading Rate in million gallons (MG), given the following:

- Land Application Acreage: 120 acres
- Soil Type: Quincy
- Effective Root Depth: 60 inches
- Precipitation in NGS, from DEQ Guidance: 5.78 inches
- Evapotranspiration in NGS, from Agrimet: 4.82 inches

1. Determine the Available Water-Holding Capacity of the Soil (AWC):

   Referring to the soil survey report, the AWC data for the Quincy soil type is:

   0 – 9 inches, AWC = 0.095 in/in

   9 – 60 inches, AWC = 0.10 in/in

   Therefore, AWC = 9 inches x 0.095 in/in + 51 inches x 0.10 in/in

   = 5.96 inches

2. Calculate NGS Hydraulic Loading Rate:

   NGS HLR = AWC + ET - Precipitation

   = 5.96 in + 4.82 in – 5.78 in

   = 5.00 inches

3. Convert to million gallons:

   NGS HLR = (5.00 in)(27,154 gal/ac-in)(120 ac)

   = 16,300,000 gallons = 16.3 MG

Plant Available Nitrogen Calculations

Some wastewater land application systems handle wastewater with high nitrogen concentrations. These systems should evaluate wastewater application rates based on supplying crop nitrogen needs rather than on the amount of water the soil-crop system can handle. Plant available nitrogen is calculated as shown in Equation 10-6.

$$PAN = [MR \times (TKN - NH_3)] + [(1\text{-}VR) \times (NH_3)] + [NO_3 + NO_2]$$

Equation 10-6. Calculation of Plant Available Nitrogen (PAN).

Where:

PAN = Plant Available Nitrogen

MR = Mineralization Rate

VR = Volatilization Rate

TKN = Total Kjeldhal Nitrogen

NH_3 = Ammonia Nitrogen Concentration

NO_3 = Nitrate Nitrogen Concentration

NO_2 = Nitrite Nitrogen Concentration

VR = 0.50 for all treatment types

MR = 0.4 for primary treatment
0.3 for aerated lagoons and sand filters
0.2 for aerobic treatment/activated sludge systems

This PAN formula simplifies toEquation 10-7.

$$PAN = [MR \times (TKN - NH_3)] + [0.5 \times (NH_3)] + [NO_3 + NO_2]$$

Equation 10-7. Simplified Calculation of Plant Available Nitrogen (PAN)

Example 8: Plant Available Nitrogen (PAN)

You are applying 15 in/acre/year to your wastewater land application field. Your irrigation wastewater contains the following concentrations:

- TKN: 56 mg/L
- Ammonia: 18 mg/L
- Nitrate: 10.5 mg/L
- Nitrite: 0.5 mg/L

Assuming a mineralization rate of 0.40, how much PAN are you applying per year to each acre?

$$PAN = [MR(TKN - NH_3)] + [0.5(NH_3)] + (NO_3 + NO_2)$$

$$PAN = [(0.40)(56 - 18)] + [(0.5)(18)] + (10.5 + 0.5)$$

$$PAN = (0.40)(38) + 9 + 11$$

$$PAN = 15.2 + 9 + 11 = 35.2 \text{ mg/L PAN}$$

Now, we need to convert mg/L to lbs using the formula:

$$\text{Pounds/year} = \text{concentration (mg/L)} * \text{Flow (million gallons per year)} * 8.34 \text{ lb/gal}$$

To do this we first need to convert our hydraulic loading rate from inches to millions of gallons.

$$\begin{aligned} \text{Flow} &= (15 \text{ in/acre})(27{,}154 \text{ gallons/acre-inch})(1 \text{ acre}) \\ &= 407{,}280 \text{ gallons/acre} \\ &= 0.407 \text{ MG/acre} \end{aligned}$$

We can now solve for lbs PAN per year on each acre:

$$\begin{aligned} \text{Lbs PAN/acre} &= (35.2 \text{ mg/L PAN})(0.407 \text{ MG/acre/year})(8.34 \text{ lb/gal}) \\ &= 119.5 \text{ lbs/acre/year PAN} \end{aligned}$$

Sodium Adsorption Ratio Calculations

The ratio of the sodium concentration to the concentrations of calcium and magnesium in the wastewater is called the *sodium adsorption ratio* (SAR). Calculations for SAR utilize the liquid concentrations (in mg/L) of sodium, calcium, and magnesium in the wastewater. The formula for Sodium Adsorption Ratio is given by Equation 10-8, with all concentrations expressed in *milliequivalents* (meq)(Equation 10-9):

$$SAR = \frac{Na}{\sqrt{0.5(Ca + Mg)}}$$

Equation 10-8. Calculation of Sodium Absorption Ratio.

$$meq = \frac{\text{concentration}}{\textit{equivalentweight}}$$

Equation 10-9. Calculation of milliequivalents.

Where:

- SAR = Sodium Adsorption Ratio
- Na = Sodium Concentration (meq)
- Ca = Calcium Concentration (meq)
- Mg = Magnesium Concentration (meg)

Example 9: Sodium Absorption Ratio (SAR)

- What is the SAR for a wastewater that has the following ion concentrations:
  Sodium (Na^+) = 84 mg/L
  Calcium (Ca^{2+}) = 23 mg/L
  Magnesium (Mg^{2+}) = 14 mg/L

The equivalent weights of sodium, calcium, and magnesium are, respectively, 23, 20, and 12.

First, convert concentrations to milliequivalents (meq):

$$Na^+ = \frac{84 \text{ mg/L}}{23} = 3.7$$

$$Ca^{2+} = \frac{23 \text{ mg/L}}{20} = 1.2$$

$$Mg^{2+} = \frac{14 \text{ mg/L}}{12} = 1.2$$

$$SAR = \frac{Na}{\sqrt{0.5 \text{ x } (Ca + Mg)}}$$

$$SAR = \frac{3.7}{\sqrt{0.5 \text{ x } (1.2 + 1.2)}} = \frac{3.7}{\sqrt{0.5 \text{ x } (2.4)}}$$

$$= \frac{3.7}{\sqrt{1.2}} = \frac{3.7}{1.1} = \boxed{3.4}$$

Wastewater Application Rate Calculations

The formulas for determining wastewater application rates were covered in Section 7 and are included again here.

Example 10 Irrigation Rate for Stationary Sprinklers

- A stationary sprinkler has a discharge rate of 17.6 gpm and a wetted diameter of 140 ft. If the sprinkler spacing is set at 60% of the wetted diameter and lateral spacing is 84 ft, what is the irrigation rate in in/hr?

First, determine the design sprinkler spacing:

Sprinkler spacing = 140 ft x 0.6 = 84 ft

Next, determine the irrigation rate using the following formula:

$$\text{Irrigation rate (in/hr)} = \frac{96.3 \text{ x discharge rate (gpm)}}{\text{sprinkler spacing (ft) x lateral spacing (ft)}}$$

$$= \frac{96.3 \text{ x } 17.6 \text{ gpm}}{84 \text{ ft x } 84 \text{ ft}} = \boxed{0.24 \text{ in/hr}}$$

Example 11: Irrigation Rate for Stationary Sprinklers

- A stationary sprinkler has a discharge rate of 13.0 gpm and a wetted diameter of 127 ft. If the sprinkler spacing is set 70 ft and the lateral spacing is set at 80 ft, what is the irrigation rate in in/hr?

$$\text{Irrigation rate (in/hr)} = \frac{96.3 \text{ x discharge rate (gpm)}}{\text{sprinkler spacing (ft) x lateral spacing (ft)}}$$

$$= \frac{96.3 \text{ x } 13.0 \text{ gpm}}{70 \text{ ft x } 80 \text{ ft}} = \boxed{0.22 \text{ in/hr}}$$

Example 12: Run Time for Stationary Sprinklers

- If a stationary sprinkler has an irrigation rate of 0.26 in/hr and your target application depth is 0.25 inches, what is the run time for the sprinkler?

$$\text{Time of Operation (hours)} = \frac{\text{target application depth (in)}}{\text{irrigation rate (in/hr)}}$$

$$= \frac{0.25 \text{ in}}{0.26 \text{ in/hr}}$$

$$= \boxed{1 \text{ hr}}$$

Example 13: Run Time for Stationary Sprinklers

- If a stationary sprinkler has an irrigation rate of 0.22 in/hr and your target application depth is 0.75 inches, what is the run time for the sprinkler?

$$\text{Time of Operation (hours)} = \frac{\text{target application depth (in)}}{\text{irrigation rate (in/hr)}}$$

$$= \frac{0.75 \text{ in}}{0.22 \text{ in/hr}}$$

$$= \boxed{3.4 \text{ hr}}$$

Crop Yield and Crop Uptake Calculations

Many wastewater land application permits specify the maximum nitrogen (and sometimes phosphorus) loading rates as 125% or 150% of typical crop uptake values. *Typical Crop Uptake* is defined as the median constituent crop uptake from the three (3) most recent years the crop has been grown. Typical Crop Uptake is determined for each hydraulic management unit (typically a single field at a land application site). For new crops having less than three years of on-site crop uptake data, regional crop yield data and typical nutrient content values, or other values approved by DEQ may be used.

Example 14: Crop Yield and Crop Uptake

Determine the Maximum Nitrogen Loading Rate in lb/ac/yr given:

- Permitted maximum nitrogen loading rate is 125% of crop uptake
- Two cuttings of alfalfa this year:
  - Cutting #1: Dry Yield of 2.8 ton/acre;
  - Cutting #2: Dry Yield of 3.7 ton/acre
- Plant Tissue Analysis Results, Dry Protein Percentage
  - Cutting #1: Dry Protein Percentage of 11.7%
  - Cutting #2: Dry Protein Percentage of 12.9%
- Conversion Factors for % Protein to % TKN:
  - Small grain: 5.72
  - Other Plant Tissue (including alfalfa): 6.25
- Plant Tissue Analysis Results, Dry Nitrate-N Concentration:
  - Cutting #1: Dry Nitrate-N Concentration of 2,860 ppm
  - Cutting #2: Dry Nitrate-N Concentration of 2,150 ppm

Note: Crop Yield and Nitrogen percentage data must be on the same moisture basis

1. Convert % Protein to % TKN:

   Cutting #1: 11.7% Protein / 6.25 = 1.87% TKN

   Cutting #2: 12.9% Protein / 6.25 = 2.06% TKN

2. Convert Nitrate-N Concentration from ppm to %:

   Cutting #1: 2,860 ppm / 10,000 = 0.286 % Nitrate-N

   Cutting #2: 2,150 ppm / 10,000 = 0.215 % Nitrate-N

3. Calculate Total % Nitrogen:

   Cutting #1: 1.87 % + 0.286 % = 2.156% Total Nitrogen (0.02156)

Cutting #2: 2.06 % + 0.215 % = 2.275% Total Nitrogen (0.02275)

4. Calculate Crop Nitrogen Uptake:

   Cutting #1: (2.8 ton/ac) x (2,000 lb/ton) x (0.02156) = 121 lb N/ac

   Cutting #2: (3.7 ton/ac) x (2,000 lb/ton) x (0.02275) = 168 lb N/ac

5. Calculate Total Crop Nitrogen Uptake:

   121 lb N/ac + 168 lb N/ac = 289 lb/ac/yr

6. Calculate Maximum Nitrogen Loading Rate:

   1.25 x 289 lb/ac/yr = 361 lb/ac/yr Total Nitrogen

References:

State of North Carolina, 2001. Spray Irrigation System Operators Training Manual.

State of Idaho, Department of Environmental Quality, 2005. Wastewater Land Application Permit Rules (IDAPA 58.01.17).

State of Idaho, Department of Environmental Quality. Guidance for Land Application of Municipal and Industrial Wastewater - October 2004